Controller HIL Testing of Real-Time Distributed Frequency Control for Future Power Systems

E. Guillo-Sansano, M.H. Syed, A.J. Roscoe, G. Burt
Institute for Energy and Environment
University of Strathclyde
Glasgow, Scotland

Mark Stanovic and Karl Schoder
Center for Advance Power Systems
Florida State University
Tallahassee, FL, USA

***Abstract*—With the evolution of power system components and structures driven mainly by renewable energy technologies, reliability of the network could be compromised with traditional control methodologies. Therefore, it is crucial to thoroughly validate and test future power system control concepts before deployment. In this paper, a Controller Hardware in the Loop (CHIL) simulation for a real-time distributed control algorithm concept developed within the ELECTRA IRP project is performed. CHIL allows exploration of many real-world issues such as noise, randomness of event timings, and hardware design issues that are often not present on a simulation-only system. Octave has been used as the programming language of the controller in order to facilitate the transition between software simulation and real-time control testing. The distributed controller achieved frequency restoration with a collaborative response between different controllers very fast after the unbalanced area is located.**

***Index Terms*—Distributed control, CHIL, frequency control, real-time simulation, octave.**

I. INTRODUCTION

It is a fact that the power system is experiencing a transition period where the share of intermittent converter connected generation and consumption (wind, solar, EVs, etc.) into different voltage levels of the power system is continuously increasing every year and with it the power system dynamics and attributes are also being modified. Large conventional rotating generator units are expected to be few compared with smaller distributed energy resources (DER). DER's are connected to the grid mostly through power converters, hence they cannot provide inertia response in the same way as large synchronous generators usually do because they are decoupled from the network. This is introducing new questions and concerns for ensuring the reliability and security of power supply because the control of systems with large penetration of renewables is more complex than previously [1]. In order to cope with the risks associated with the obvious development of the power system network new control solutions are required for providing a stable and secure service. ELECTRA (European Liaison on Electricity Committed Towards long-term Research Activity) Integrated Research Programme is one of such projects intended to help with the transition towards future power systems, where more decentralized generation connected to distribution systems is expected along with an increased observability and control at the lower voltage levels [2]. These characteristics encourage the search for novel architectures such as the Web of Cells (WoC) [2], shown in Fig.1, where novel frequency and voltage control concepts can be developed for future power systems due to its distribution of areas. As an example ELECTRA IRP is aiming for a more local control approach for resolving voltage and frequency contingencies with the help of the decentralized characteristic of future power systems. The increased complexity and variability of future electricity grids bring the opportunity for the development of distributed control approaches that can reduce the complexity of the system by solving issues in a local manner. In contrast with centralized control approaches less observability and communication is required (per controller) and also frequency and voltage control could be implemented on a smaller scale.

The development of novel distributed grid intelligence concepts is a complex design task that requires coordination between different engineering domains such as control, power systems and data communication [3]. Once the design

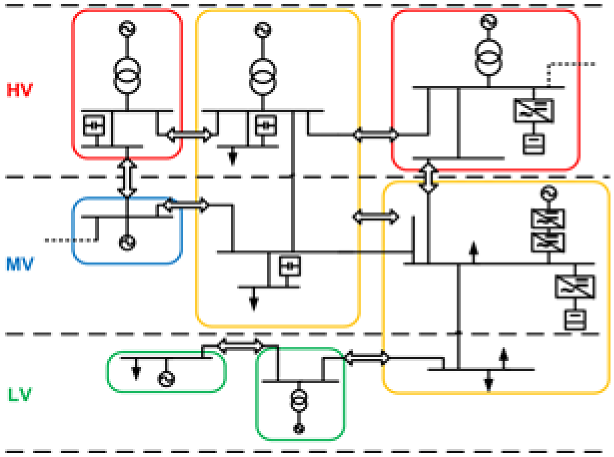

Fig. 1 Web of Cells structure example

The work in this paper has been supported by the European Commission, under the FP7 project ELECTRA (grant no: 609687). Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the European Commission.

of the control algorithms is at an advanced stage, testing and validation of these concepts plays an important role in the final design and verification of the concepts.

Controller Hardware in the Loop (CHIL) is a widely established testing technique for controller development and validation where the components and dynamic behavior of the power system is simulated in real-time and the simulation is coupled to a real hardware controller [4]. This technique allows fast implementation of power system control testing with reduced costs and risks over hardware testing. It also allows to experiment with real-world issues such as noise, hardware weakness, randomness of event timings or communication issues. Smart grid testbeds for testing advance control logic [5][6], are a development of CHIL for distributed control algorithms with advanced control logic and large-scale data communication.

In this paper, a CHIL simulation of a novel distributed frequency control algorithm is implemented in a smart grid testbed. The control algorithm has been implemented in Octave due to its compatibility with MATLAB and, being a higher-level language, it facilitates quickly implementing algorithm prototypes. In Section II the distributed control scenario used for the CHIL testing is presented. Section III describes the setup used for performing the CHIL simulation. The experimental process and results are presented in Section IV. Finally, the conclusions and lessons learned are summarized in Section V.

II. DISTRIBUTED CONTROL SCENARIO

The WoC architecture has been developed in the interest of reducing the complexity of distributed approaches and facilitating transition towards the replacement of classical centralized control of power systems. This is achieved by dividing the power system into smaller controllable sections, known as cells, with well-defined electrical and geographical boundaries, shown in Fig.1. Cells also have local observability and control. A cell can span across multiple voltage levels and is interconnected with other cells through tie-lines that allow for network reconfiguration if required. Also, it is expected that internal cell problems will be solved as locally as possible and by coordinating actions with neighboring cells when needed. This approach maintains the locality of the response and also improves the efficiency of the overall power systems as distances from source to load will be reduced reducing losses in the system.

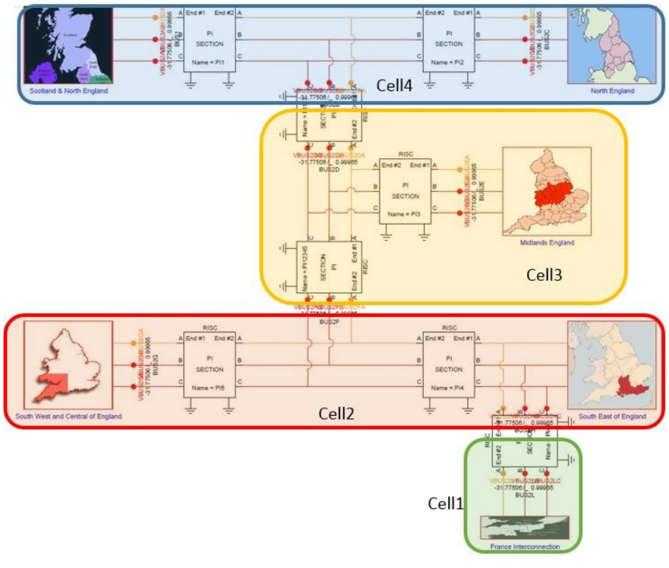

Fig. 2 Four cell power system model

Power system frequency is known as a global parameter across synchronous regions of the grid. This factor increases the complexity of distributed frequency control as the coordination between multiple controllers and the speed of reaction is crucial for the correct control operation of the network. Frequency management strategies under contingency can vary across different synchronous regions, mainly they differ on the timescale of the different procedures but all of them have common characteristics.

Usually, primary frequency reserve is activated for controlling the frequency deviation after a contingency but it does not restore the frequency to operation level. This is usually carried out by the governor action of the generators. Within ELECTRA IRP two different controllers have the purpose of substituting the primary control [7]. The first one will be responsible of reducing the Rate of Change of Frequency (RoCoF) and therefore reducing the slope at which frequency is falling, synthetic inertia [8] from power converters along with governor action from conventional generators (lower share in the future) will provide this response. Along with the inertia response, Frequency Containment Control (FCC) will contain the frequency with the automated response of power devices activated according to local frequency measurements.

Secondary frequency reserve aims to restore the frequency to operational levels by activating reserves in a centralized manner. The proposed comparable control designed within ELECTRA is called Balance Restoration Control (BRC), they share the same objective but BRC intends to do it in a distributed manner and by observing the balance in power exchange in its own cell instead of the frequency as it will try to solve the frequency contingency in a localized manner. This controller is the one that has been developed to be evaluated in a CHIL environment for this paper. The controller is divided into two phases, a procurement phase and a real-time operation phase.

a) Procurement phase

The procurement phase objective is to gather the required reserve amount for the next period of time, this being defined as a time in which predictions on intermittent generation and flexibility of devices can be accurate and at the same time gives enough time for the procurement process. An estimated period for procurement of reserves in the future could be around a 30 min time window. The output of the procurement phase will be a contingency plan, so if an event occurs after the automated reserves have actuated, the cell can restore normal operating conditions by following the contingency plan. The procurement phase is divided into intra-cell procurement and inter-cell procurement of reserves as shown in Fig.3. Intra-cell procurement only takes into account the available resources within the cell in order to keep the

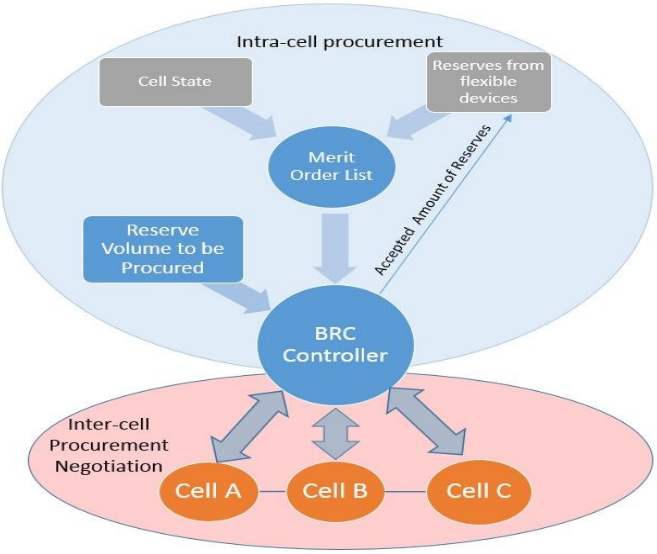

Fig. 3 Procurement phase structure

procurement as local as possible. For this process, a merit order list of available energy resources arranged by ascending order of price is built with inputs from measurements of the cell state (or cell state estimation) and the available flexibility from the resources. Once the merit order list is built the BRC controller will compute the net amount of reserves.

If the cell has either in excess or deficiency of reserves, the cell controller will inform its neighbor cells of its status (either excess or deficit of reserves) and at this point the intra-cell procurement negotiation phase will start. During this phase all the cell controllers will negotiate with their neighbors in a distributed manner similar to [9], where they will try to find the cheapest reserves from their neighbors taking into account the constraints of the system. The negotiation will finish once all the cells have managed to procure enough reserves, it is assumed that enough reserves will be available. Then, the BRC controller will send a reserve acceptance or rejection signal to the flexible devices that were participating so they can be prepared for the next period.

b) Real-time operation phase

The real-time operation phase continuously checks the status of the cell balance, which is the difference between the reference tie-line power flows for the period and actual tie-line power flows between the cell and its neighbors. When an unbalance is detected by the BRC controller of the cell, it sends commands to activate its local reserves and informs any neighbors that had negotiated to supply reserves; thereby, restoring frequency to the proper operational level.

III. CHIL SETUP

One of the main differences between all computer simulation and a CHIL simulation is the required lab setup in order to perform the tests along with the added complexity of real hardware and communications adding unknown behaviors. At the same time CHIL is closer to a real implementation and therefore it's a step forward towards the final design of control algorithms. For the testing of the frequency control prototype, a CHIL simulation was implemented in a smart grid testbed [6][7]. The main components of the CHIL environment used simulation of this work are:

A. Real-time simulation.

The Real Time Digital Simulator (RTDS) is a powerful simulation tool for performing real time power system simulations developed by RTDS Technologies [10]. It is composed of a modular custom computing hardware with a parallel processing architecture. Depending on the application different processing and I/O cards can be enclosed in each module, also called racks. A common communication backplane connects multiple racks allowing large power system simulations to simultaneously use multiple racks. The simulation time step for the tests carried out in this paper is 50µs. The processor cards used for this experiment are a Giga Processor Card (GPC) and a Gigabit Transceiver Network Interface (GTNET) card; the GPC card contains two processors.

A reduced dynamic model of the United Kingdom (UK) power system developed on RSCAD (software interface tool for the RTDS) was used for the simulation and is mapped to four cells power system according to the WoC concept, the model is shown in Fig.2. For this stage of the design of the controller the six zones present on the model correspond to an area of the UK and have an aggregated generator model and the corresponding aggregated load of the area, this will reduce the complexity of the model focusing only on the controller behavior and distributed response. So, each of the cells will be controlled independently and exchanging signals with its own controller.

B. Control Boards and algorithm

Octave [11] has been used as the programming language for developing the control algorithm because of its compatibility with Matlab and its high-level language favorable for prototyping. Matlab user interface also offers a helpful environment for programming prototypes that can accelerate the design of the control algorithms. However, Octave is not fully compatible with Matlab and some of the mathematic and communication functions used in the algorithm required modifications for running successfully on Octave.

Each of the cells is independently managed by a controller running a control algorithm for its own cell. All four cell controllers will perform a negotiation for achieving a local contingency plan for potentially large frequency deviations happening at some point during the period following the negotiation. So there will always be a contingency plan ready (although only for N-1 situations at the moment). The period is intended to be large enough so that the negotiations are not time constrained. The real-time phase is more time sensitive as the speed of the response affects the effectiveness of responding to a frequency event. Nevertheless, the BRC controller is assumed to be activated after automatic response from primary controllers. But there is a chance that this controller achieves faster responses and could possibly replace or work together with faster automatic controllers reducing the number of them and increasing the speed of the response.

The code for four cells has been implemented on four embedded single board computers called Mamba designed by Versalogic Corporation [12]. Each Mamba board has a dual-core processor running at 2.26GHz with 2GB of memory and two Gigabit Ethernet ports for communication. The characteristics of the Mamba boards allow for implementations of control prototypes in higher-level languages including Octave, Matlab, and Python.

C. Communication interfaces

Communication plays an important role in distributed algorithms as it is crucial for maintaining the correct operation of the system. It is also expected that with the increase of distributed devices along with an increased observability of the network more advanced and complex communications systems will exist in the future.

For the implementation of the distributed frequency control case two different communication paths are used: inter-cell communication (between the cell controllers) for negotiation of reserves and communication between cell controllers and the power system (Mamba board and RTDS).

1) Communication between cell controllers for negotiation.

The Mamba boards communicate with each other via Ethernet through a switch as shown in Fig.4. This communication structure allows communication from one board to any other board, however for efficiency and locality of the solution for the distributed frequency algorithm tested in this paper, only communication with the neighboring cells is implemented. In the case of a cell not being able to find enough reserve from its neighbors a communication to the neighbors of neighbors could be implemented. The communication between cells for negotiation was implemented using User Datagram Protocol (UDP).

2) Communication between controllers and real-time simulation for CHIL.

Traditional CHIL simulations are usually connected through analog signals or to just one hardware device. However for a distributed control approach where digital signals are transferred from the simulation to the controller's appropriate distribution of the signals is required. The signals to be transmitted from the power system need to be allocated to the particular cell controllers and separated from the signals going to a different cell controller. This is a complex task for the GTNET card and so for this purpose a server is introduced between the simulation and the distributed controllers, the server will receive all the signals from the power system simulation that are sent from the GTNET card using the socket protocol. The server will be responsible for the precise distribution of the signals coming from different cells of the power system, the server code will route the signals to their corresponding cell controllers according to a configuration file. Hence, the controllers can independently read the signals coming from their cell area. This communication structure will allow the CHIL implementation of distributed control algorithms. In this case the GTNET card, the server and the mamba cards are communicating through TCP/IP to ensure that the messages are received.

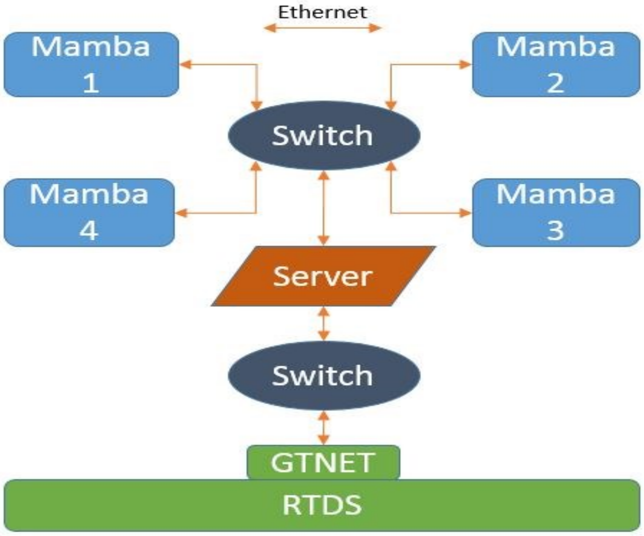

Fig. 4 CHIL Communication Structure

Once the communication is established the data formats that both parts of the CHIL simulation (RTDS model and mamba boards) accept need to be analyzed. In this case the GTNET card can only send and receive integer and floating point numbers and these are represented as 4-bytes in the packet. The data points in the GTNET card are stored in big endian format. On the other hand Octave sockets package can only receive 8-bit unsigned integers (uint8) and the data is stored in little endian format.

This mismatch of data formats and endianness requires extra lines of code for adapting the data that is sent and received. For this matter on the controller side when the data is read from the server first of all it needs to be split in groups of 4-bytes as each 4-bytes composes a different signal, then each of the 4-bytes groups is currently a 4 separated uint8 signals that need to be converted into a single uint32 before its bits are swapped for going from big endian to little endian. For the process of sending data from the controllers to the server, calculations on the controller code are usually carried out with single or double precision numeric data types, therefore before data is sent it need to be converted to uint8 without changing underlying data. On the server side the same process but opposite is performed, the received data at the server from the RTDS is converted from a single precision number to a uint8 and the received uint8 is converted to single and also swapped.

IV. RESULTS OF CHIL TESTING

The power system model shown in Fig. 2 is used for the CHIL testing of the control. The reserves required for each cell for the next period could be calculated in different manners. Actually it is based on the N-1 scenario of losing the largest generator on the network, however for a scenario such as the web of cells calculating it based on the largest generator could lead to a redundant excess of reserves on the network.

Deterministic forecasts methods of operating reserve are simple and straightforward to calculate. However, they do not take into account the variability and intermittency of wind, uncertainty in the demand forecast or the probability of unpredicted equipment failures. Therefore, system operators need to adapt the methodology for establishing the level of operating reserve in order to ensure the reliability and availability of the power system. For the purpose of testing the controller, how this value is calculated is not critical although it is acknowledged as a research opportunity.

Therefore for this scenario the cells have been defined as cells with excess or deficit of reserves. Cell 1 has deficit of 500MW, Cell 2 has excess of 1500MW, Cell3 has deficit of 1500MW and Cell 4 has excess of 1500MW. This values are very large but have been selected in order to have a more complex negotiation, but also for making the frequency going out of the operation range of 49.9-50.2Hz and showing how the cooperation between the neighbors can help.

The combined characteristics of the generators and loads along with the total power transfer going in or out of each cell are presented on Table 1, were net power transfer is negative represents a cell importing power. The inertia constant of the generators on the network is 4MWs/MVA.

Table 1 Cell electrical characteristics.

	Generation (MW)	Consumption (MW)	Power transfer (MW)
Cell 1	1220	0	1220
Cell 2	19670	29000	-10608
Cell 3	8890	8390	361
Cell 4	29950	20700	9005

The generators on the network have a 5% droop assigned in order to provide the primary response for the activation, once the frequency is contained, the BRC controller will activate the required reserves to restore the frequency to operational levels.

First of all the simulation requires to be run until the frequency is stable around 50Hz. Once the frequency is stable and the power system is running in normal conditions the controllers are started. The controllers will then know how much is their deficit or excess and will start the negotiation. As a result from the experiment Cell 2 will provide 500MW of reserves to Cell 1 and Cell 2 and Cell 4 will provide 500 and 1500 respectively to Cell 3 if required. This negotiation takes between 0.1 and 0.5 seconds.

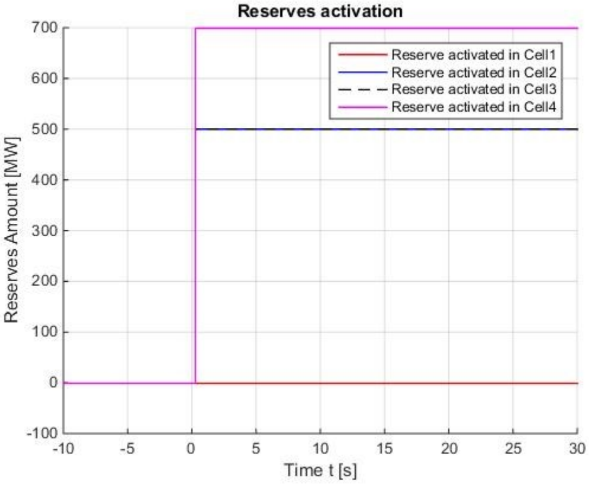

Fig. 5 Reserves activation

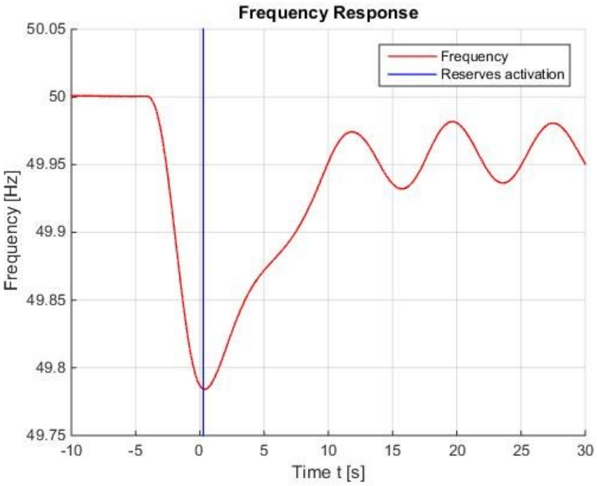

Fig. 6 Frequency Response

After all the cells manage to get enough reserves for the next period, the negotiation is finished and during the next period the controller will analyze the cell balance by measuring the power flow and comparing it with the reference for the period plus the response provided by the droop control. Once the cell has detected the unbalance within its cell and the frequency goes beyond the operation zone is when non dynamic frequency response such as the BRC control is activated, before that point dynamic frequency controllers are supposed to be continuously controlling the frequency. At this point the cell controller will send a signal to the other cells with the amount required for the particular event that will be according to the measured unbalance and each cell controller will activate the requested reserves within its cell. The cell controllers can update the status of the network every 1-1.5ms although such a fast update rate might not be required for large transmission systems.

When a loss of generation of 1700MW occurs in Cell 3, the location is identified by the cell controller when the conditions are met for 0.2 seconds, then the controller request for 500MW to Cell 2 (as this one is cheaper) and the rest to Cell 4 as shown in Fig.5. Cell 3 also has 500MW of reserves within its cell. All of them send the request to change the load at almost the same time and it takes less than 0.1 seconds for the devices providing reserves to receive it. In this case the loads automatically respond to the request, although a rate limiter of 20MW per second is introduced for reducing the overshoot and to account for slower response loads.

The frequency that in normal conditions was at 50Hz, after the loss of generation goes below 49.8Hz as shown in Fig.6, the time 0 in the figure represents when the unbalance is detected for the first time (0.2s later is when the activation signal is sent to the other cell controllers if the conditions are still applying). When the inertia and droop control have reduced the RoCoF and maintained the frequency, the set-point from the controllers will drive the amount of flexible loads providing the requested amount of reserve, as a result of this action the frequency goes back to 49.7Hz after some oscillations between 50 and 49.9Hz.

V. CONCLUSIONS

CHIL provides a great opportunity for developing and testing distributed control algorithms in a more realistic environment than pure simulations. The communication setup of distributed control algorithms for CHIL simulations has proven to be more complex. Octave has exhibit a good performance as a tool for fast prototyping of algorithms developed with Matlab and its higher-level language allows to redefine the design conveniently. This early simulation results have shown that the distributed control algorithm with localized frequency response could be a solution for future power systems. However, the quantification of reserves for each cell needs further study as deterministic quantification methods may not be the best solution for future power systems. The development of the CHIL testing in this paper will provide a starting point for an implementation of a distributed frequency control scenario in the WoC architecture on a Power Hardware in the Loop (P-HIL) simulation were real devices could be directly controlled instead of simulated in real-time.

VI. ACKNOWLEDGMENT

This work is supported by the European Community's Seventh Framework Program (FP7/2007-2013) under project "ELECTRA IRP" (Grant Agreement No. 609687).

VII. REFERENCES

[1] M. Yu, A. Dysko, C. Booth, A.J. Roscoe, J. Zhu, H. Urdal, "Investigations of the constraints relating to penetration of non-synchronous generation (NSG) in future power systems." *Sixth Protection, Automation and Control World Conference (PAC World 2015)*

[2] L. Martini, L. Radaelli, H. Brunner, C. Caerts, A. Morch, S. Hanninen, and C. Tornelli, 2015, "ELECTRA IRP approach to voltage and frequency control for future power systems with high DER penetrations", *Proceedings of 23rd International Conference on Electricity Distribution (CIRED), Lyon.*

[3] E. Guillo-Sansano et al., "Transitioning from Centralized to Distributed Control: Using SGAM to Support a Collaborative Development of Web of Cells Architecture for Real Time Control" *in Proc. of the CIRED Electricity Distribution Workshop, 2016, in press.*

[4] A.J. Roscoe, E. Guillo-Sansano and G. Burt, (2016) "Physical Hardware in the Loop Modelling and Simulation". In Smart Grid Handbook. Liu, C-C. (Ed.). John Wiley & Sons Inc.

[5] M. Stanovich, I. Leonard, K. Sanjeev, M. Steurer, T. Roth, S. Jackson, and B. McMillin, "Development of a Smart-Grid Cyber-Physical Systems Testbed," in *Proc. of the IEEE PES Innovative Smart Grid Technologies (ISGT)*, Feb. 2013.

[6] K. Schoder, Z. Cai, S. Sundararajan, M. Yu, M. Sloderbeck, I. Leonard, and M. Steurer, "Real-Time Simulation of Communications and Power Systems for Testing Distributed Embedded Controls," *Institution of Engineering & Technology (IET)*, Jan. 2016.

[7] R. D'hulst et al., "Voltage and frequency control for future power systems: the ELECTRA IRP proposal," *Smart Electric Distribution Systems and Technologies (EDST), 2015 International Symposium on, Vienna, 2015, pp. 245-250.*

[8] D. Remon, A. M. Cantarellas, E. Rakhshani, I. Candela and P. Rodriguez, "An active power self-synchronizing controller for grid-connected converters emulating inertia," *Renewable Energy Research and Application (ICRERA), 2014 International Conference on,* Milwaukee, WI, 2014, pp. 424-429.

[9] M. Chen, M. H. Syed, E. Guillo Sansano, S. D. J. McArthur, G. M. Burt, "Distributed Negotiation in Future Power Networks: Rapid Prototyping Using Multi-Agent System" in *Proc. of the IEEE PES Innovative Smart Grid Technologies (ISGT), 2016.*

[10] RTDS Technologies, http://www.rtds.com.

[11] J.W. Eaton, D. Bateman, S. Hauberg, R. Wehbring, (2015). *GNU Octave: a high level interactive language for numerical computations*. (4th ed.) [Online]. Available: https://www.gnu.org/software/octave/octave.pdf

[12] Versalogic Mamba Board, "Mamba EBX SBC with Intel Core 2 Duo," http://versalogic.com/products/DS.asp?ProductID=215.